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MEASUREMENTS AND OBSERVATIONS OF NOISE FROM
A 4.2 MEGAWATT (WTS-4) WIND TURBINE GENERATOR

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INTRODUCTION

Noise measurements and calculations are being made for large wind turbine generators to develop a data base for use in designing and siting such systems for community acceptance (Refs. 1-11). As part of this program, measurements were made on the WTS-4 wind turbine generator during its acceptance runs. This paper presents the results of these exploratory measurements for power output conditions in the range 1.0 to 4.2 MW. Data include noise levels, spectra, radiation patterns, effects of distance, and the associated perception thresholds for use in the further development of acceptance criteria for this type of machine (Ref. 12).

This effort is part of the Department of Energy wind energy program which is managed by the NASA Lewis Research Center. The WTS machine was manufactured by the Hamilton Standard Division of United Technologies and is currently operated by the Department of the Interior, Bureau of Land Management.

APPARATUS AND METHODS

Description of Site

Measurements were made at the operational site of the WTS-4 machine near Medicine Bow, Wyoming (see Fig. 1). The site is located in gently rolling open range territory that has an elevation of about 2075 m (6800 ft.) above sea level and is remote from airports and main highways. There are no trees and only sparse surface vegetation.

Wind velocity and direction were monitored and recorded continuously from meteorological instruments located at an elevation of 80 m and at a distance of about 300 m west (upwind) of the machine. For all data reported herein the wind direction varied from 250° to 300° , the wind velocity ranged from 7.6 m/s to 21 m/s (17 to 47 mph), the relative humidity varied from 44% to 76%, the barometric pressure varied from 772 mB to 798 mB, and the ambient temperature varied from 0° to 10°C . All data were recorded on October 26-28, 1982 and between 1000 and 1700 hours.

Description of Wind Turbine Generator

The WTS-4 wind turbine generator has a two bladed, 79.2 m (256.6 ft.) diameter, rotor mounted on an 80 m (263 ft.) high tower with a twelve sided cross section. The distance across the tower, between flats, is 3.66 m (12 ft.) It is a downwind machine (inflow encounters the tower first before encountering the rotor) having a rated power output (P) of 4.2 MW. Its operational range of wind velocities (V) is about 7.1 m/s to 27 m/s (15.9 to 60.4 mph). The blades are pitch controlled at the root by a hydraulic control system and rotational speed is maintained at 30 rpm. Blades are tapered in chord from 1.04 m (3.4 ft.) at the tip section (NACA 23012 airfoil) to 4.69 m (15.4 ft.) at the root section (NACA 23036 airfoil). The twist angle varies from approximately -1° at the tip to 16° near the root. Figure 2 shows photographs of the machine for the feathered condition and for operation at rated power. Note that under full power conditions the blade-tower clearance varies from about 5 m at the root to about double that amount at the tip. Figure 3 presents sample 200 sec duration recorded traces of output power, wind speed and wind direction relative to the nacelle yaw position during routine operations at near rated power.

Acoustic Measurements and Observations

All noise measurements were made with commercially available battery powered instrumentation. One half inch diameter condenser microphones with a useable frequency range 3-20,000 Hz were used with two different tape recording systems. One of the systems included a two channel direct recording machine which provides a useful dynamic range of about 100 dB in the frequency range of 25 Hz to 20,000 Hz. This system provided high dynamic range recordings for possible use in subjective listening tests. The other system included an FM four channel recorder having a useful dynamic range of about 40 dB in the frequency range of 0 Hz to 15,000 Hz. For some recordings the microphone signals to both recorders were C-weighted in attempts to more effectively utilize the available dynamic ranges. Sound pressure level measurements were also taken with a precision sound level meter on the linear scale as well as for weighting networks A and C.

Data were obtained for distances up to about 900 m (2950 ft.), and at various azimuth angles from 0° (on axis upwind) to 180° (on axis downwind). The measurement locations for both tape recordings and sound level meter readings are shown in Figure 4. Sound spectral data were obtained with the aid of conventional one-third octave band and narrow band analyzers.

To minimize the detrimental effects of wind noise, polyurethane foam microphone wind screens were used and microphones were placed near the ground surface, where wind velocities were relatively low.

Measurements and listening observations were made in the far acoustic field during routine operations in order to define the extent to which the wind turbine noise is detectable above the background noise upwind, downwind and to the side of the machine.

RESULTS AND DISCUSSION

Noise data presented herein were obtained from measurements made with precision sound level meters, and from FM and direct tape recordings. Data are presented in the form of pressure time histories, narrow band frequency spectra, one-third octave band frequency spectra, amplitude distributions and overall linear, C-weighted and A-weighted levels. In addition some aural observations are summarized to indicate the approximate distances at which the wind turbine noise can be detected above the background noise.

Sound Pressure Time Histories

Sound pressure time history data are included in Figures 5-8. Example pressure wave forms are given in Figure 5 for a distance of 91.5 meters upwind of the machine during normal operations. Shown are four pressure pulses which were observed to be associated with the passages of the blades through the wake of the tower. Note the substantial variability in the wave forms from one blade passage to another. Succeeding passages of a given blade are seen to produce widely different wave forms and associated peak values of the instantaneous pressure. Note, for example, the wave form differences for the two passages of blade number 2. The reasons for such wide variability are not known but are believed to be associated with differences in the flow encountered by the blades as they traverse the tower wake. Such flow differences may arise from variations in both the direction and velocity of the wind which in turn can cause rotor blade lift and drag variations. The data of Figure 5 and associated observations strongly suggest that the so called "thumping" noise of the machine is associated with the interactions of the blades with the aerodynamic wake of the tower.

Similar wave form variability was also observed in the downwind and crosswind directions as illustrated in Figure 6. Tracings of sixteen second duration oscillograph records are presented to illustrate the variability and other features of the wave forms. At all distances for which records were made, wave form variations were noted to occur in much the same manner as is illustrated in Figure 6. Note that the peak pressure values are noticeably lower for the crosswind condition. In order to investigate the possibility of recurring flow structure, a much longer time history record was analyzed in Figure 7.

The data points of Figure 7 are the peak levels of the positive excursions of the instantaneous pressures for an 8 minute sample containing 480 successive blade passages. The points are connected by straight lines as an aid in reading the figure. The wide amplitude variations seem to be random in nature.

The amplitude distribution of the data of Figure 7 is plotted in Figure 8. Shown on the vertical scale are the percentages of the total sample which have peak positive values at given peak sound pressure levels. For instance there were 12 percent of the total or 68 peaks having a peak level between 94-95 dB. Likewise, it can be seen that there is an extreme range of peak levels of about 15 dB, and that 93 percent of the data falls in the range of 90-100 dB (peak).

The shape of the distribution of Figure 8 is not statistically different from normal, thus suggesting a random process.

Narrow Band Spectra

Magnetic tape recordings for several of the measuring points were analyzed on a narrow band basis to identify discrete frequency components. These results are shown in Figures 9 through 12. The data of Figure 9 give comparisons of the spectra obtained for three different directions from the machine at a constant distance of 91.5 m. The spectra shown are very similar in nature. Note that a large number of harmonics of the blade passage frequency (1 Hz) are evident. Their amplitudes are highest at the low frequencies and generally decrease as frequency increases. Exceptions are those components which coincide in frequency with the shaft speed of the electric generator (30 Hz) and its harmonics (Figure 9). Comparisons of the levels of corresponding low frequency components indicate that the upwind values are comparable to the downwind values. Noticeably lower values are associated with the crosswind orientation. This result suggests that the discrete frequency components which are observed as "thumping" noise are directional in the upwind and downwind directions. This is consistent with similar observations for the MOD-OA machine (Ref. 9).

Similar narrow band spectral data are shown in Figure 10 for distances of 183 m and 732 m respectively. These spectra resemble closely those of Figure 9. Harmonics of the blade passage frequency are readily identifiable to about 100 Hz. Note that the recorded levels of wind turbine noise are generally above the background noise levels.

The WTS-4 machine has hydraulic pumps and cooling fans which generate measurable noise. The cooling system equipment operates intermittently as required during the operation of the WTS-4 machine. Figure 11 contains example narrow band spectra of the noise from the hydraulic pumps and cooling fans during zero rotor rotation of the machine. Several discrete frequency peaks are noted and were identified with components of the system. The noise of the pumps and fans is readily observable in the absence of blade rotation but is not observable during normal machine operation.

Figure 12 presents narrow band noise spectra for the WTS-4 machine at distances of 183 m and 732 m respectively. The low frequency (less than 100 Hz) peak contains mainly the blade passage harmonics. The remainder of the spec-

trum is largely broadband in nature with the exception of the two fan frequencies noted on the figure.

One-Third Octave Band Spectra

Broad band spectral data are shown in Figures 13 and 14. Figure 13 presents measured spectra at a distance of 91.5 m at ground level and for two different orientations. The top (shaded) area encompasses the spectra for measurement points upwind and downwind on the axis of rotation of the machine. These data are consistent with those of Figure 9 and indicate relatively small differences at the upwind and downwind locations. Likewise, the lower (hatched) area encompasses several spectra measured in the plane of rotation on both sides of the machine. Although there was variability, there were no consistent differences noted between the right and left hand sides. As in Figures 6 and 9 the in-plane levels are generally lower than the on-axis levels.

The effects of distance in the downwind direction are illustrated in Figure 14. Data are shown for distances ranging from 91.5 m to 732 m. These results are generally consistent with those of Figures 10 and 12. There seems to be an orderly reduction of sound pressure levels as a function of distance except for the data at 91.5 m. This measurement point is sufficiently close to the machine to be heavily influenced by the directivity and large dimensions of the source. Such close-in measurements should not be extrapolated to larger distances. Data for distances of 173 m or greater are believed to approximate far field conditions.

Overall Sound Pressure Levels

A large number of sound pressure levels were measured with a sound level meter to complement those data obtained by means of tape recordings. All of these data are included in Figures 15 through 17 and are shown as either A, C, or linear weightings, as appropriate, as a function of distance from the machine. The data of Figure 15 show a comparison of the A-weighted, C-weighted and linear weighted values for the WTS-4 machine. The appropriate shaded areas encompass all of the meter readings made at azimuth angles from 0° to 360°. Thus, a number of readings are plotted at each distance and the shading extends to include the extreme values recorded. The much lower values associated with

the C-weighted and A-weighted data result from the dominance of the low frequency components as noted in Figures 9-12. The linear weighted levels which contain substantial contributions from the low frequencies exhibit a lesser rate of reduction with distance than do the A-weighted values.

Figure 16 shows direct comparisons of the measured A-weighted values for the WTS-4, MOD-2 and MOD-OA machines. Some previously unpublished data are included for the MOD-2 and MOD-OA machines as well as those from References 8 and 9. The levels associated with the WTS-4 machine are generally higher than those of the other machines. Figure 17 provides comparisons of the measured overall sound pressure levels (linear) with predicted values by the method of Reference 8. The radiated sound power is assumed to be proportional to blade area and to the sixth power of blade section speed at the 0.9 radius station. No atmospheric attenuation is included in the calculations. The predicted values at a given distance are highest for the WTS-4 machine primarily because of its relatively high tip speed as indicated in the table of Figure 16. The measured data for the WTS-4 machine seem to fall above the predicted values. This is believed to result from the presence of low frequency loading noise harmonic components which are not included in the broad band noise estimate of Reference 8. A similar result is evident for the MOD-OA machine which is also a downwind configuration. The MOD-2 data on the other hand agree more closely with the predicted values. Note that the MOD-2 machine is an upwind configuration.

Radiation pattern data are shown in the polar plots of Figures 18 and 19 for A-weighted and linear weighted levels respectively. A-weighted levels are plotted for distances of 183 and 732 m in Figure 18. Data from tape records and from sound level meter readings are shown with reference to the wind vector to illustrate the directional characteristics of the radiated noise. Although some scatter is evident, it can be seen that the pattern at 183 m is generally non-directional except for a notch (lower levels) near the plane of rotation. At 732 m the levels are lower, the notch is not evident (at least in part due to turbulence scattering), and the pattern is skewed in the downwind direction. This skewness (or higher downwind levels) is believed to result from effects of the mean wind gradient. Similar data for overall (linear) sound pressure levels are given in Figure 19, and similar results are evident.

Observed Perception Distances

Attempts were made during the routine operation of the machine to observe its far field noise in directions both along its axis of rotation and in its plane of rotation with the objective of defining the extreme distances at which it could be perceived aurally. The resulting perception distances are plotted in polar form on Figure 20. The data points represent locations where the noise from the machine could be observed only intermittently. Perception distances varied from about 900 m upwind to about 1600 m crosswind to about 2900 m downwind. In the upwind and crosswind locations the perception distances were determined by the high frequency broad band noise. On the other hand, in the downwind direction the low frequency thumping noises were the dominant components. Note that the upwind shadow zone effect was more important for the lower frequencies, presumably because of a lower effective source height.

CONCLUSIONS

Measurements and observations of noise from the WTS-4 wind turbine generator for a range of wind velocities from 7.6 to 21 m/s (17 to 47 mph) and electrical power outputs in the range 1.0 to 4.2 MW suggest the following:

1. Identifiable peaks in the pressure time histories are noted as each blade passes through the tower wake. Peak levels vary from the passage of one blade to the other and from successive passages of the same blade. Their amplitude distribution is normal (Gaussian) but higher values are consistently observed in the upwind and downwind directions than in the crosswind direction.
2. The noise spectra contain identifiable components at the blade passage frequency and its harmonics up to about 100 Hz (100 harmonics). Components below about 30 Hz are relatively intense, and are readily identified at all locations at which recordings are made.
3. Near field data include identifiable components associated with the electric generator, the hydraulic pumps and the cooling fan. Of these, only the fan noise components are observable by ear in the far field.
4. Broad band noise at frequencies up to a few thousand Hertz is more intense in the upwind and downwind directions than in the crosswind direction.

5. Perception distances varied from about 900 m upwind to about 1600 m crosswind to about 2900 m downwind. Low frequency thumping noise was perceived downwind but only the higher frequency broad band components were perceived at extreme distances upwind and crossw

REFERENCES

1. Kelley, Neil: Noise Generated by Large Wind Turbines. Presented at Wind Energy Technology Conference, Kansas City, MO, March 16-17, 1981.
2. Greene, G. C.; and Hubbard, H. H.: Some Calculated Effects of Nonuniform Inflow on the Radiated Noise of a Large Wind Turbine. NASA TM 81813, 1980.
3. Martinez, Rudolph; Widnall, Sheila E.; and Harris, Wesley L.: Predictions of Low Frequency and Impulsive Sound Radiation from Horizontal Axis Wind Turbines. NASA CR 2185, February 1981.
4. Greene, G. C.: Measured and Calculated Characteristics of Wind Turbine Noise. NASA CP 2185, February 1981.
5. Viterna, L. A.: The NASA LaRC Wind Turbine Sound Prediction Code. NASA CP 2185, February 1981.
6. Balombin, J. R.: An Exploratory Survey of Noise Levels Associated with a 100 kW Wind Turbine. NASA TM 81486, 1980.
7. Keast, D. N.; and Potter, R. C.: A Preliminary Analysis of the Audible Noise of Constant-Speed, Horizontal-Axis Wind-Turbine Generators. DOE/EV-0089, US-11.60, July 1980.
8. Hubbard, H. H.; Shepherd, K. P.; and Grosveld, F. W.: Sound Measurements of the MOD-2 Wind Turbine Generator. NASA CR 165752, July 1981.
9. Shepherd, K. P.; and Hubbard, H. H.: Sound Measurements and Observations of the MOD-0A Wind Turbine Generator. NASA CR 165856, July 1981.
10. Hubbard, Harvey H.; Shepherd, Kevin P.; and Grosveld, Ferdinand W.: Noise Characteristics of Large Wind Turbine Generators. Proposed for publication in Noise Control Engineering Journal, 1983.
11. Hubbard, Harvey H.; and Shepherd, Kevin P.: Noise Measurements for Single and Multiple Operation of 50 kW Wind Turbine Generators. NASA Contractor Report 166052, December 1982.
12. Stephens, David G.; Shepherd, Kevin P.; Hubbard, Harvey H.; and Grosveld, Ferdinand W.: Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines. NASA TM 83288, March 1982.

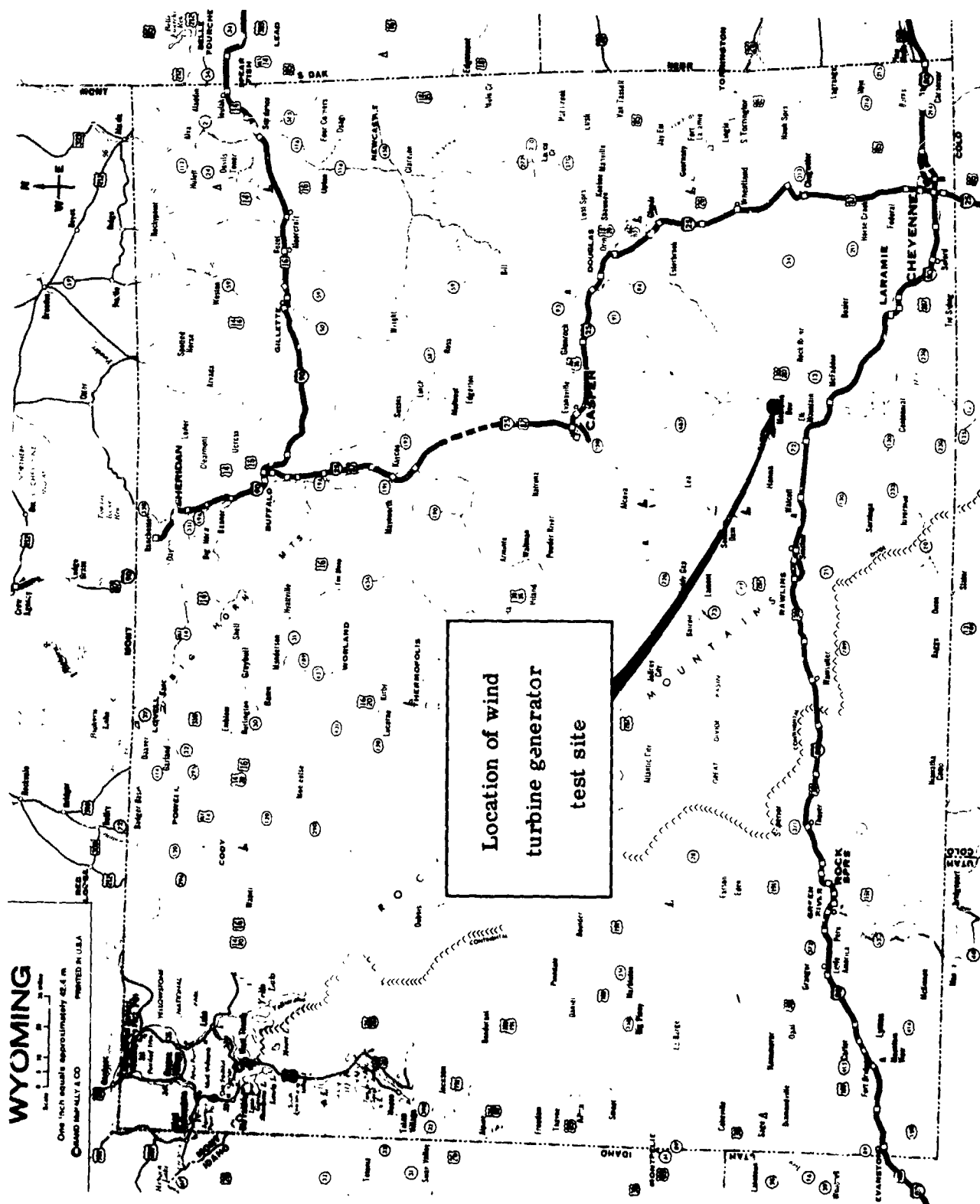
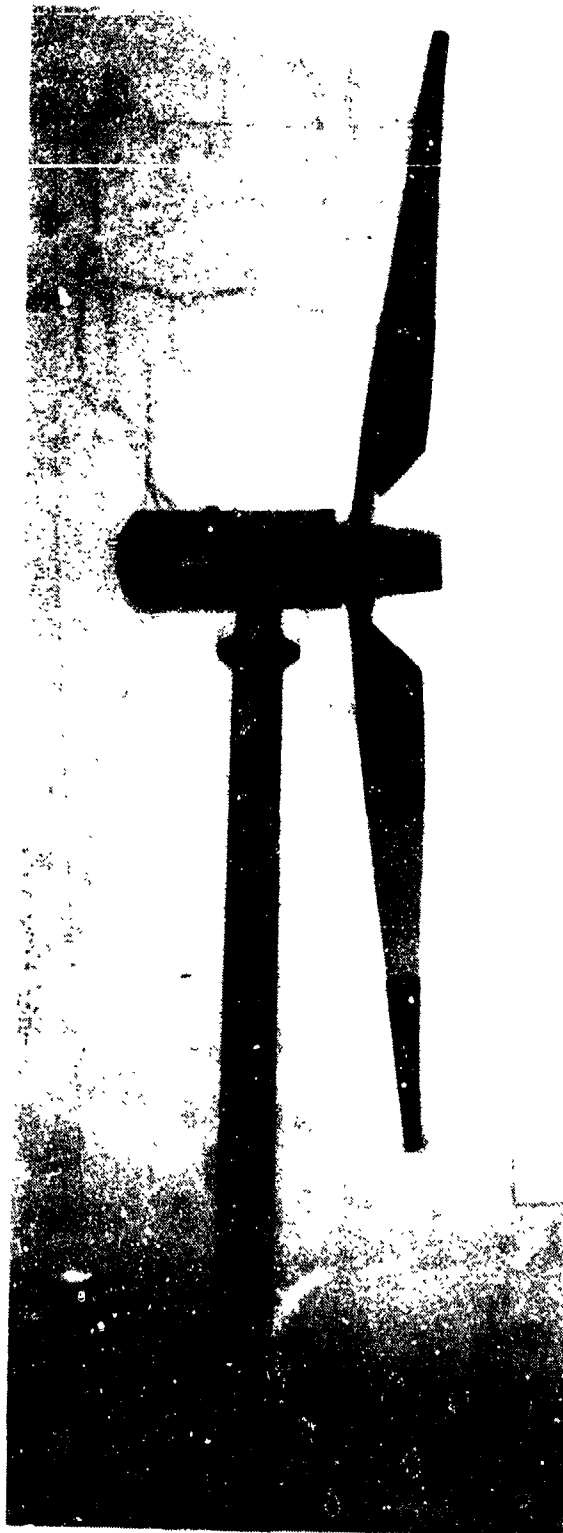


Figure 1.- Department of the Interior (DOI) Bureau of Reclamation W.S-4 wind turbine generator test site.



(a) Feathered



(b) At rated power

Figure 2.- Photographs of WTS-4 wind turbine generator.

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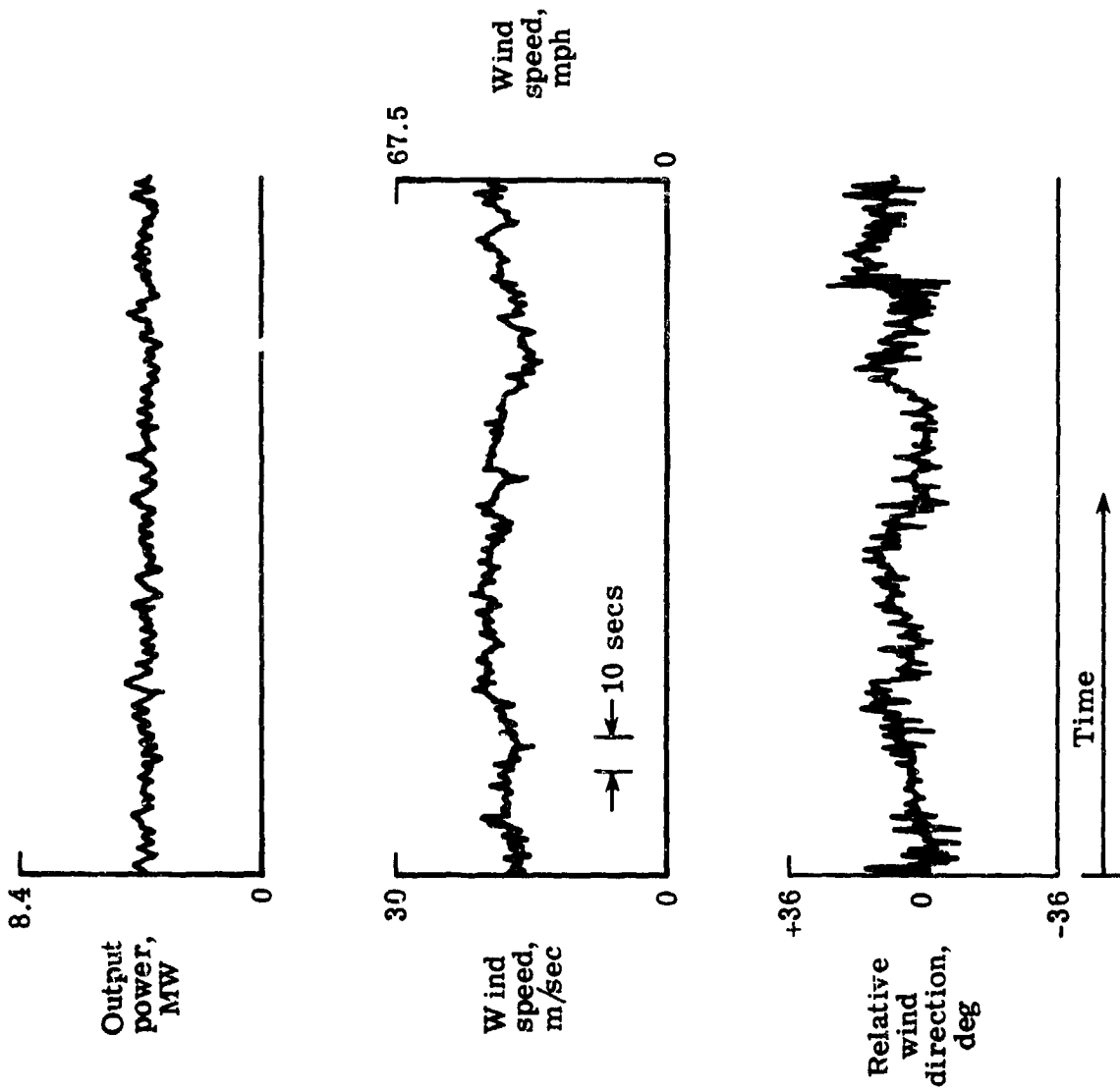


Figure 3.- Traces of oscillograph recordings of output power, wind speed and wind direction for the WTS-4 machine at near rated power.

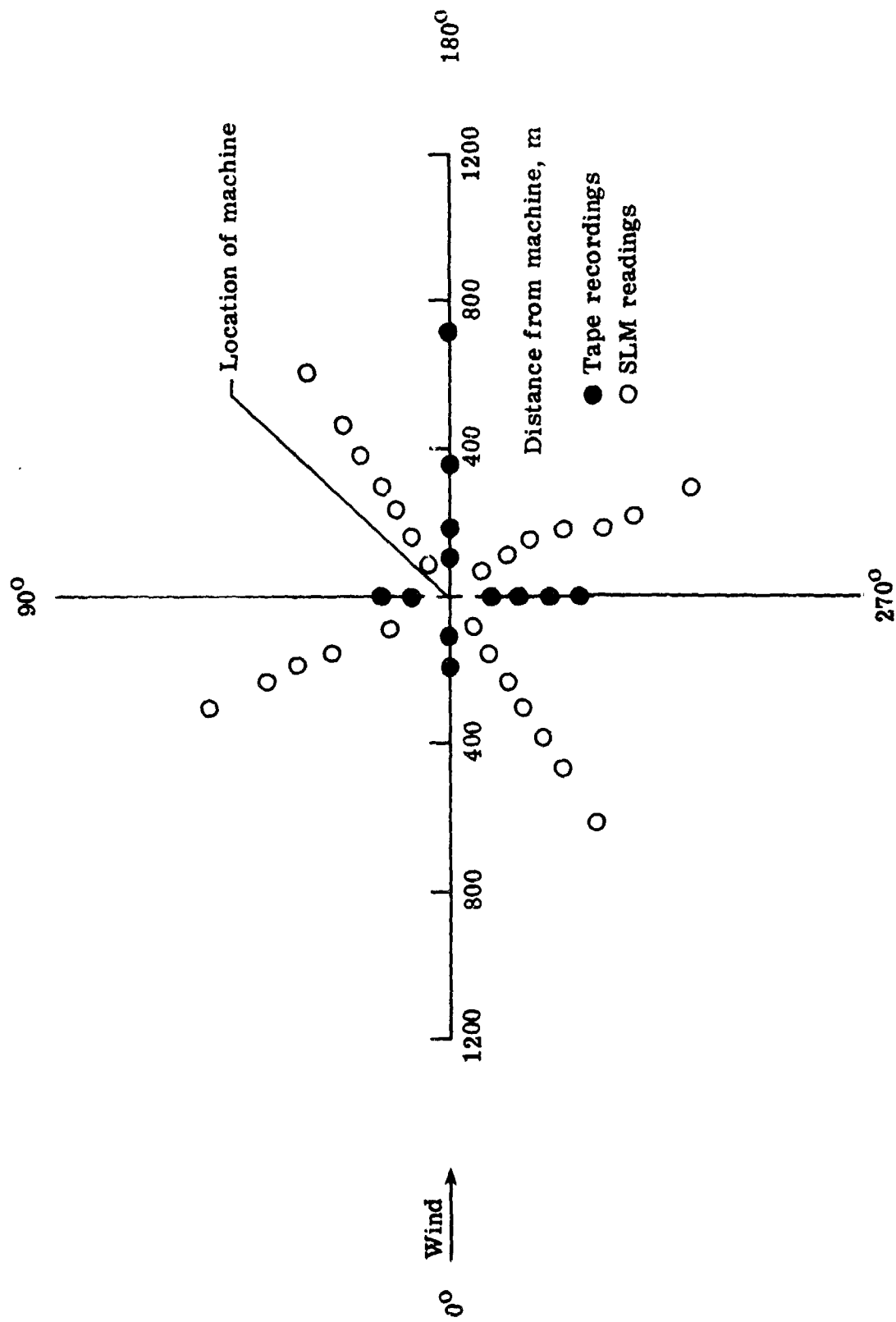


Figure 4.- Plan view sketch showing locations for which acoustic data were measured.

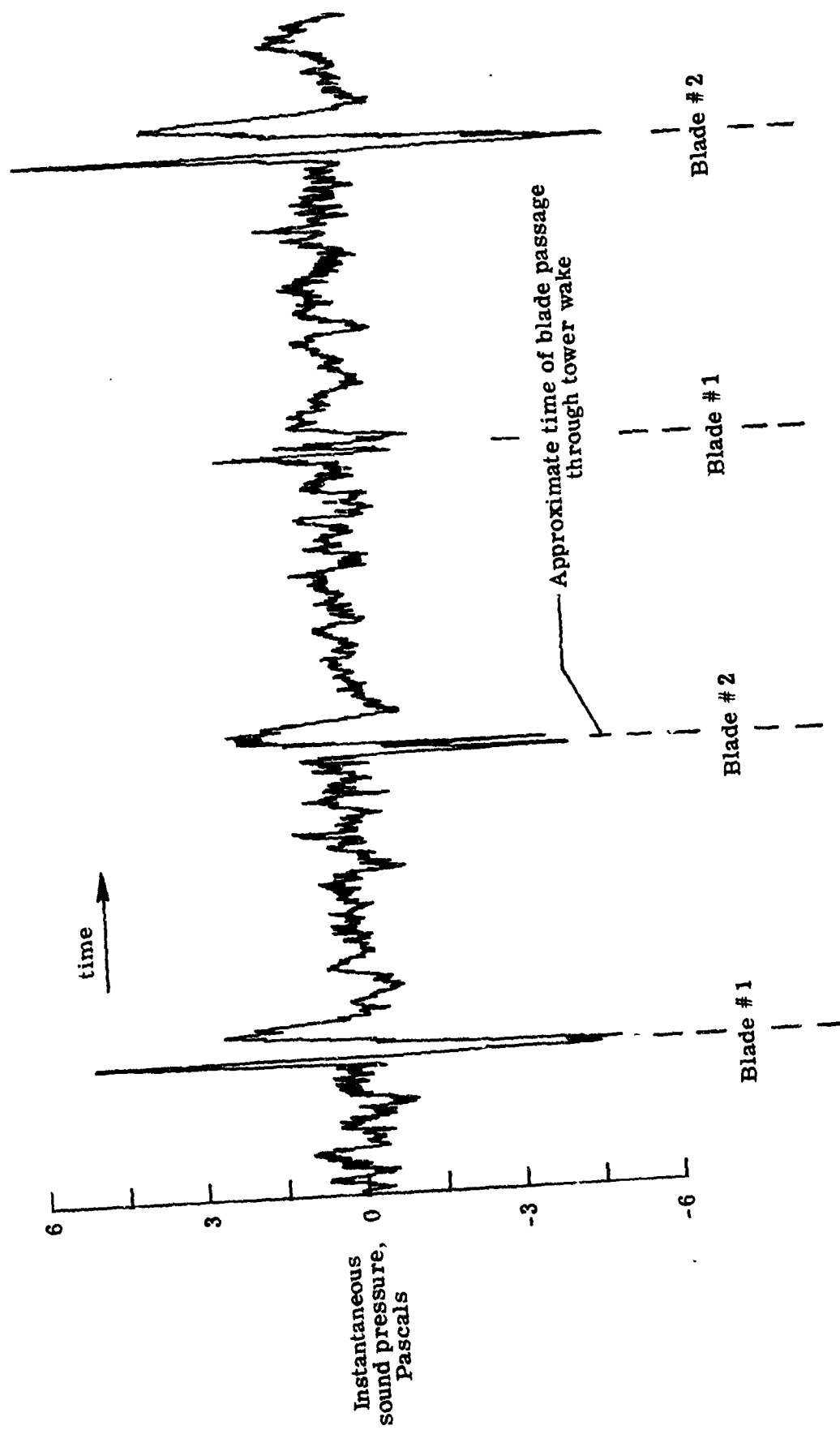
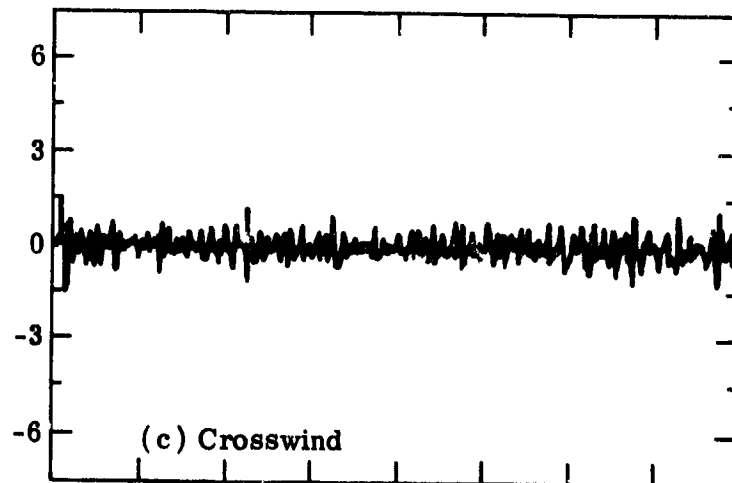
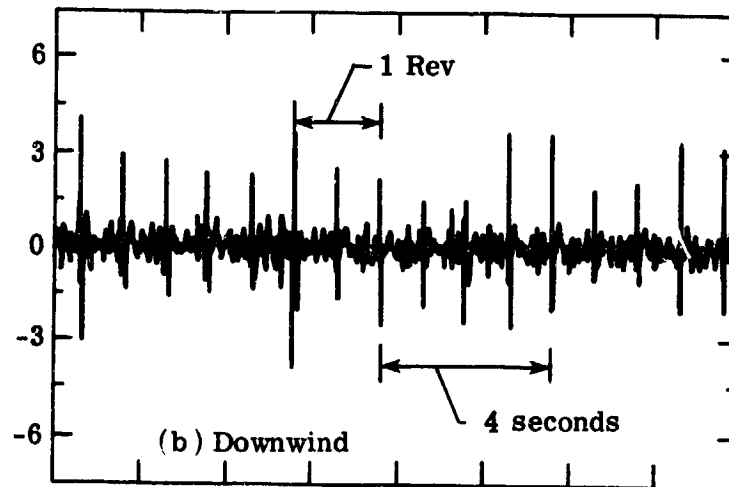
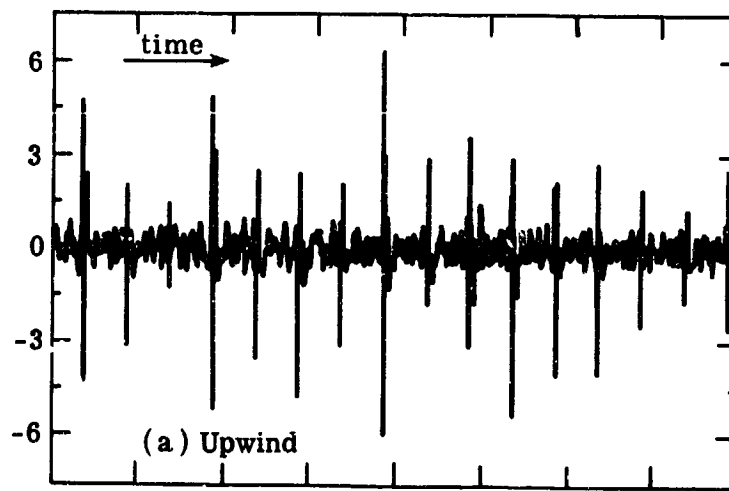


Figure 5.- Time history trace of the instantaneous sound pressure in the frequency range 3-2,000 Hz for the WTS-4 wind turbine generator. Data were recorded at a distance of 91.5 m at ground level upwind of the machine. $P = 2.4$ MW, $V = 12$ m/s.

Instantaneous
sound pressure,
Pascals



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Figure 6.- Comparisons of time history traces of the instantaneous sound pressure in the frequency range 3-2,000 Hz for the WTS-4 wind turbine generator at three locations. Distance = 91.5 m, P = 2.4 MW, V = 12 m/s.

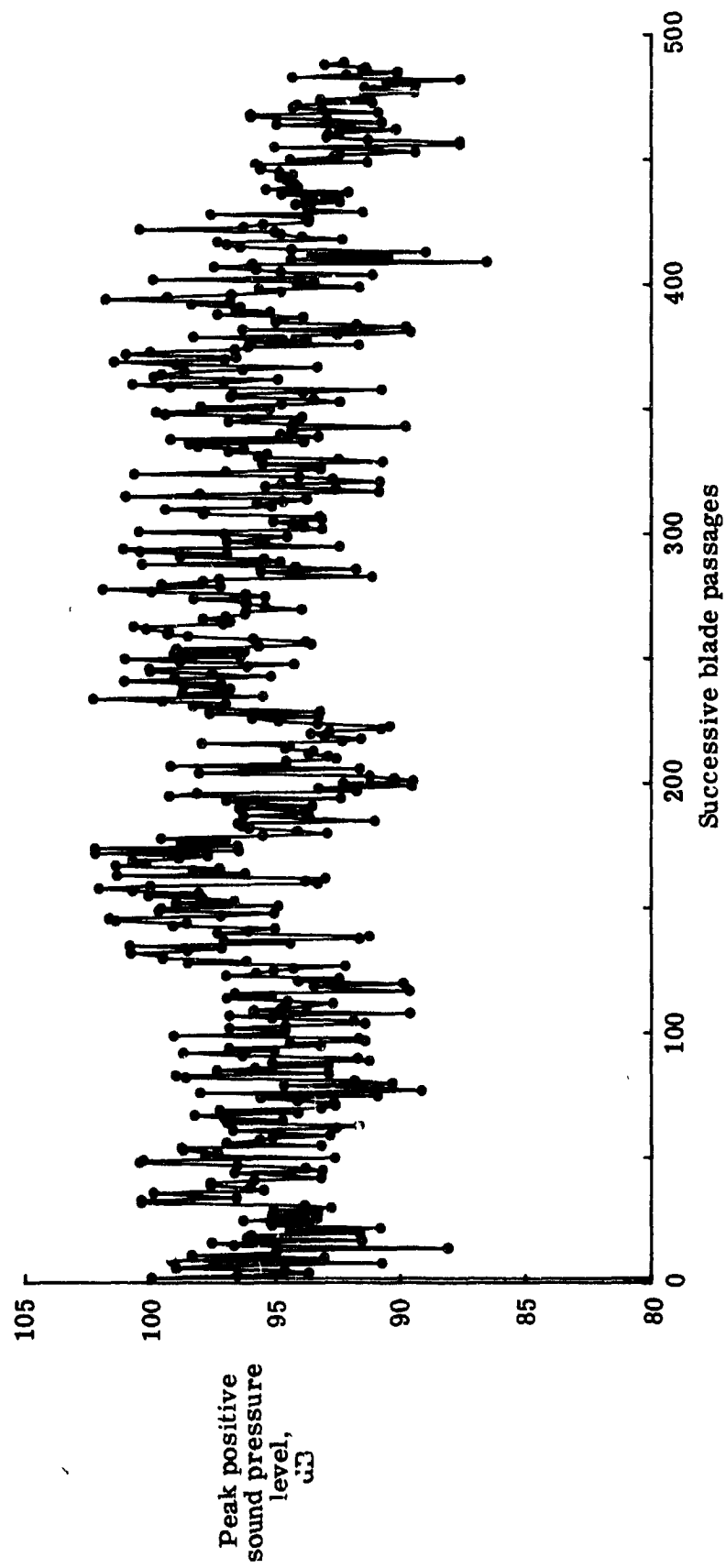


Figure 7.- Time variation of the positive peak values of the instantaneous pressure for successive blade passages. Data are for an 8 minute sample recorded at ground level, 183 m downwind of the machine. $P = 2 \text{ MW}$, $V = 17 \text{ m/s}$.

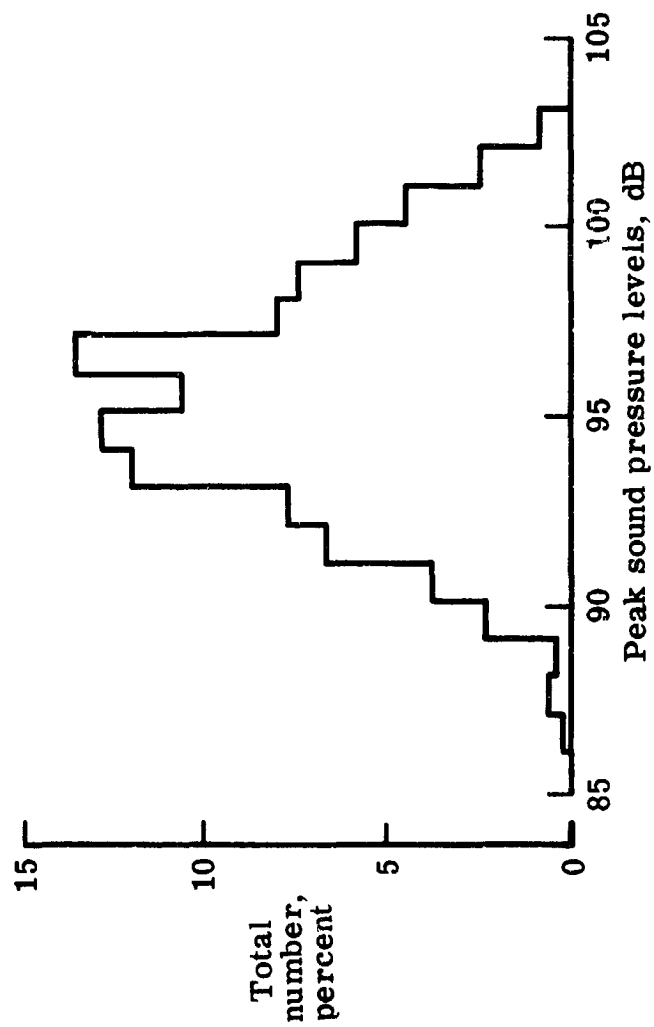
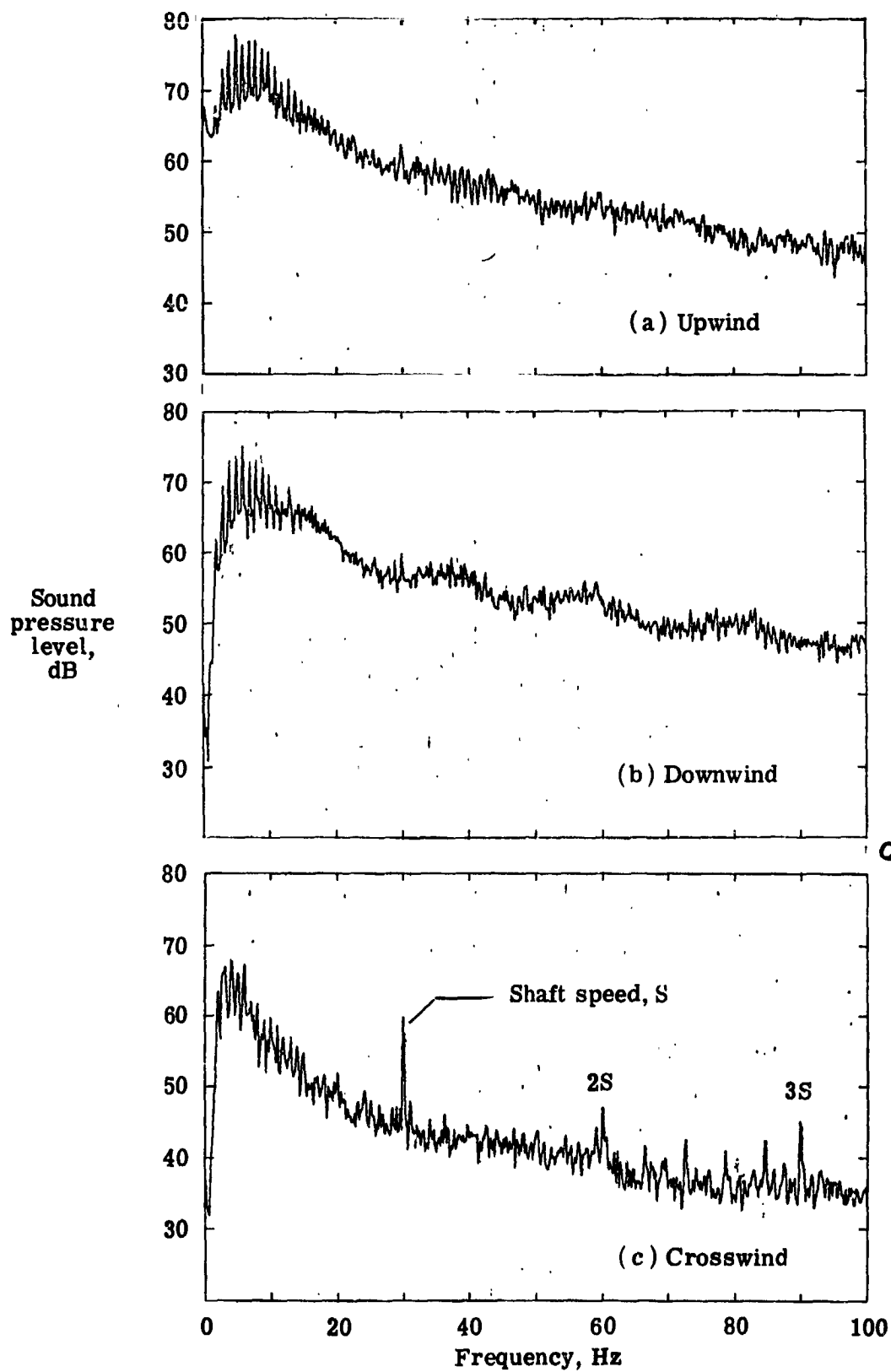


Figure 8.- Distribution of peak sound pressure levels from the data of Figure 6.



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Figure 9.- Example narrow band (0.125 Hz) spectra for three locations at a distance of 91.5 m. $P = 2$ MW, $V = 12$ m/s.

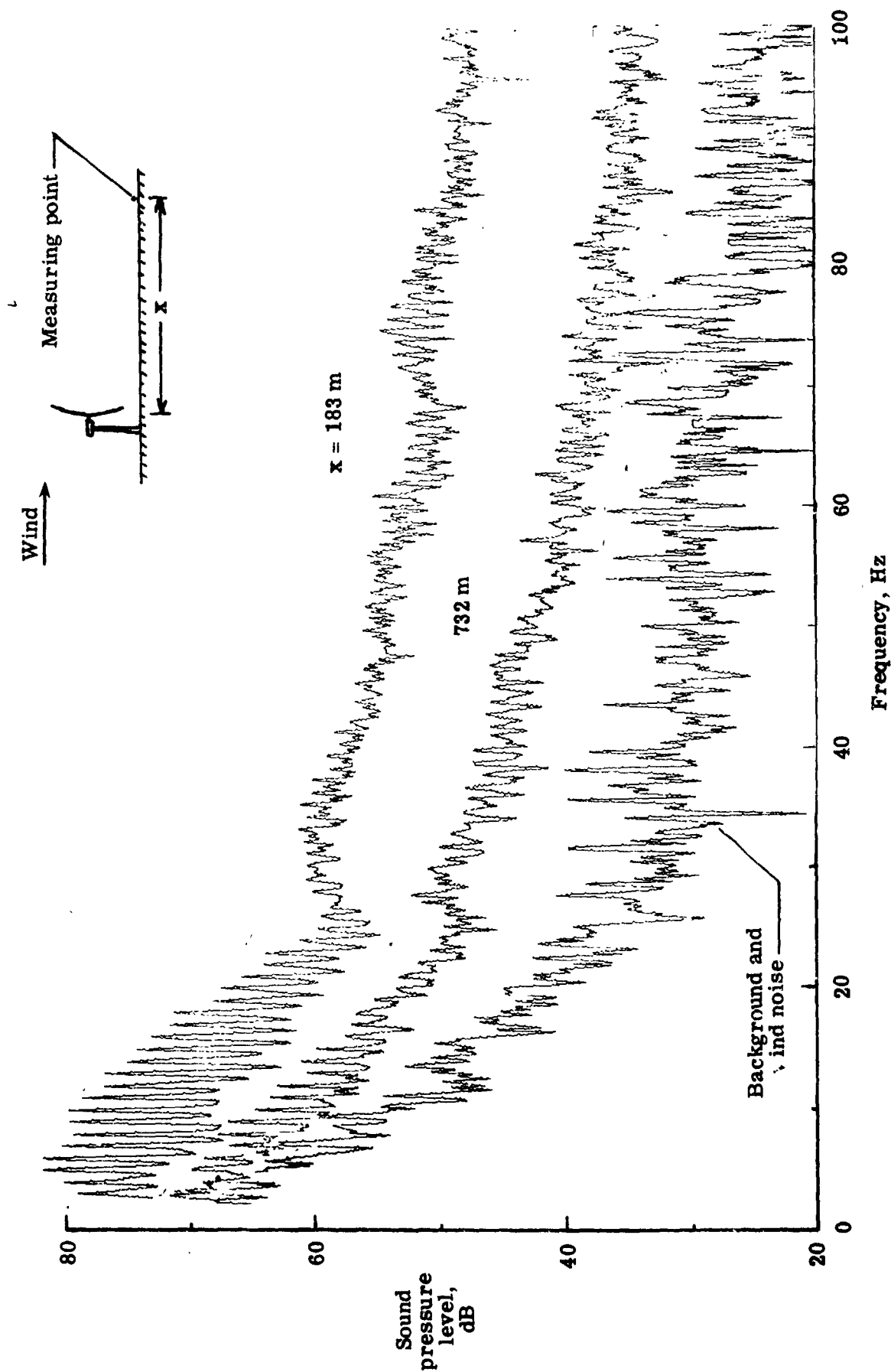


Figure 10.- Narrow band (0.125 Hz) noise spectra for WTS-4 machine at two locations in the far acoustic field. $P = 2.0\text{--}2.3 \text{ MW}$, $V = 12\text{--}17 \text{ m/s}$.

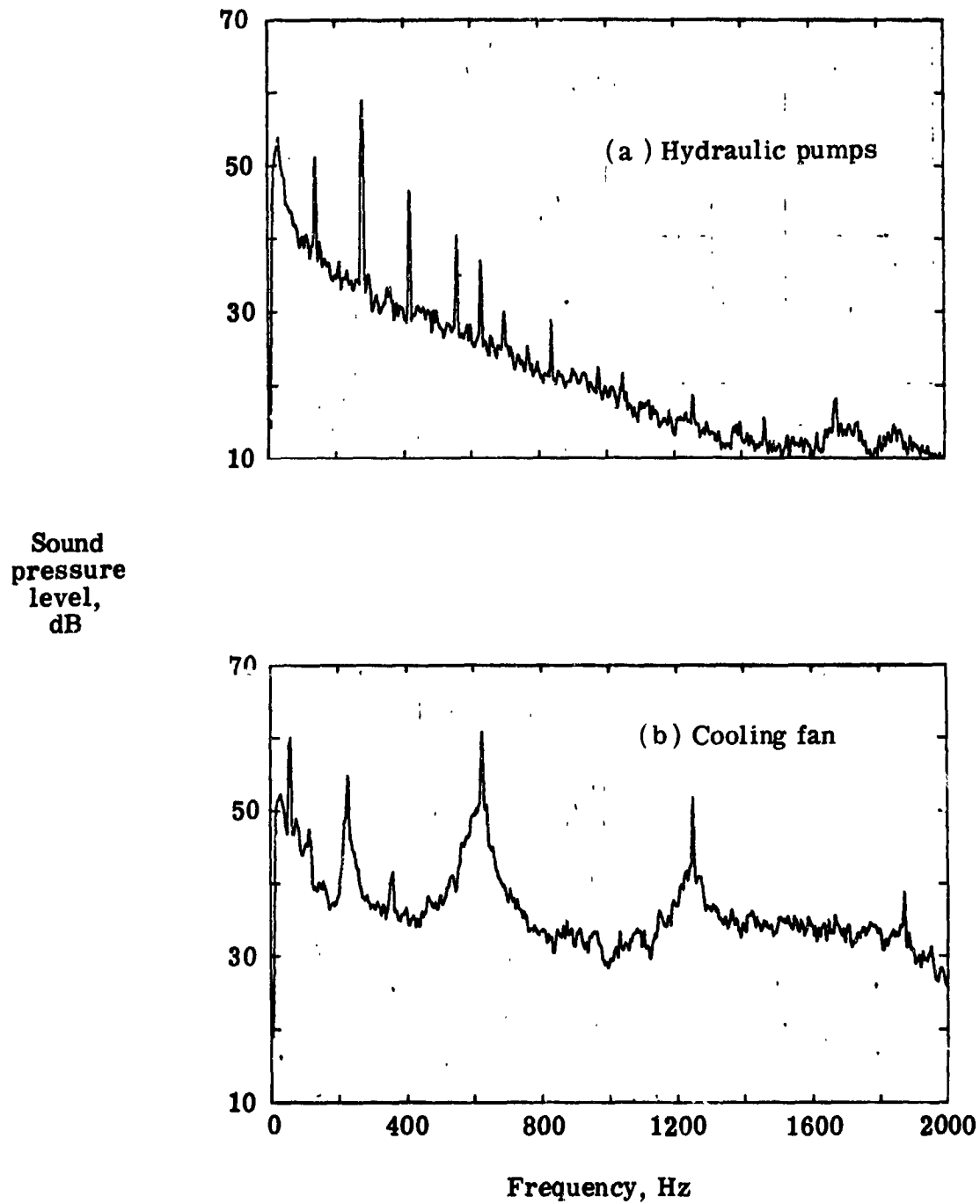


Figure 11.- Narrow band (2.5 Hz) spectra of the noise from operation of hydraulic pumps and cooling fans for WTS-4 machine at zero rotation.

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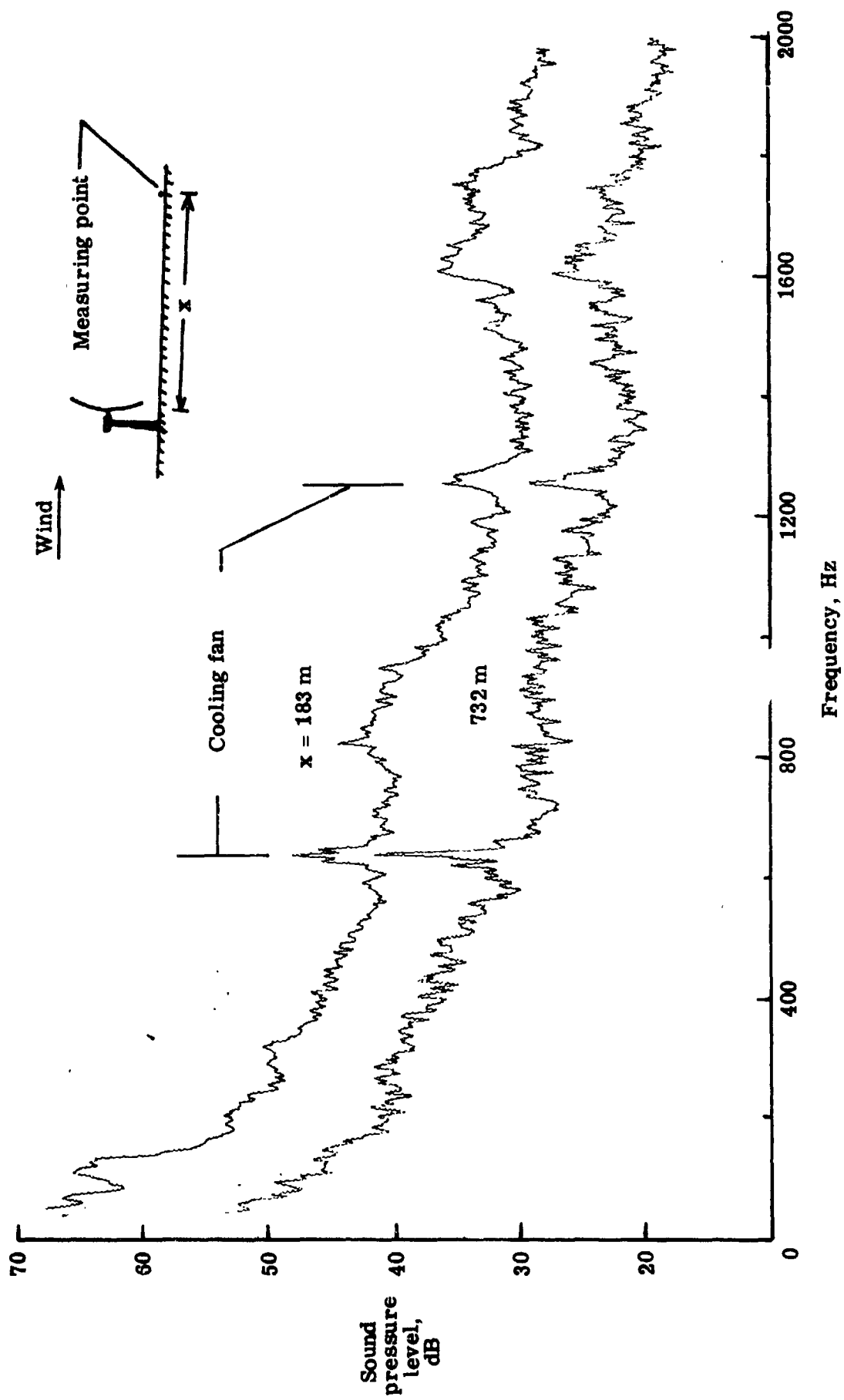


Figure 12.- Narrow band (2.5 Hz) spectra of the noise from the WTS-4 machine at two locations in the far acoustics field. $P = 2.0$ - 2.3 MW, $V = 12$ - 17 m/s.

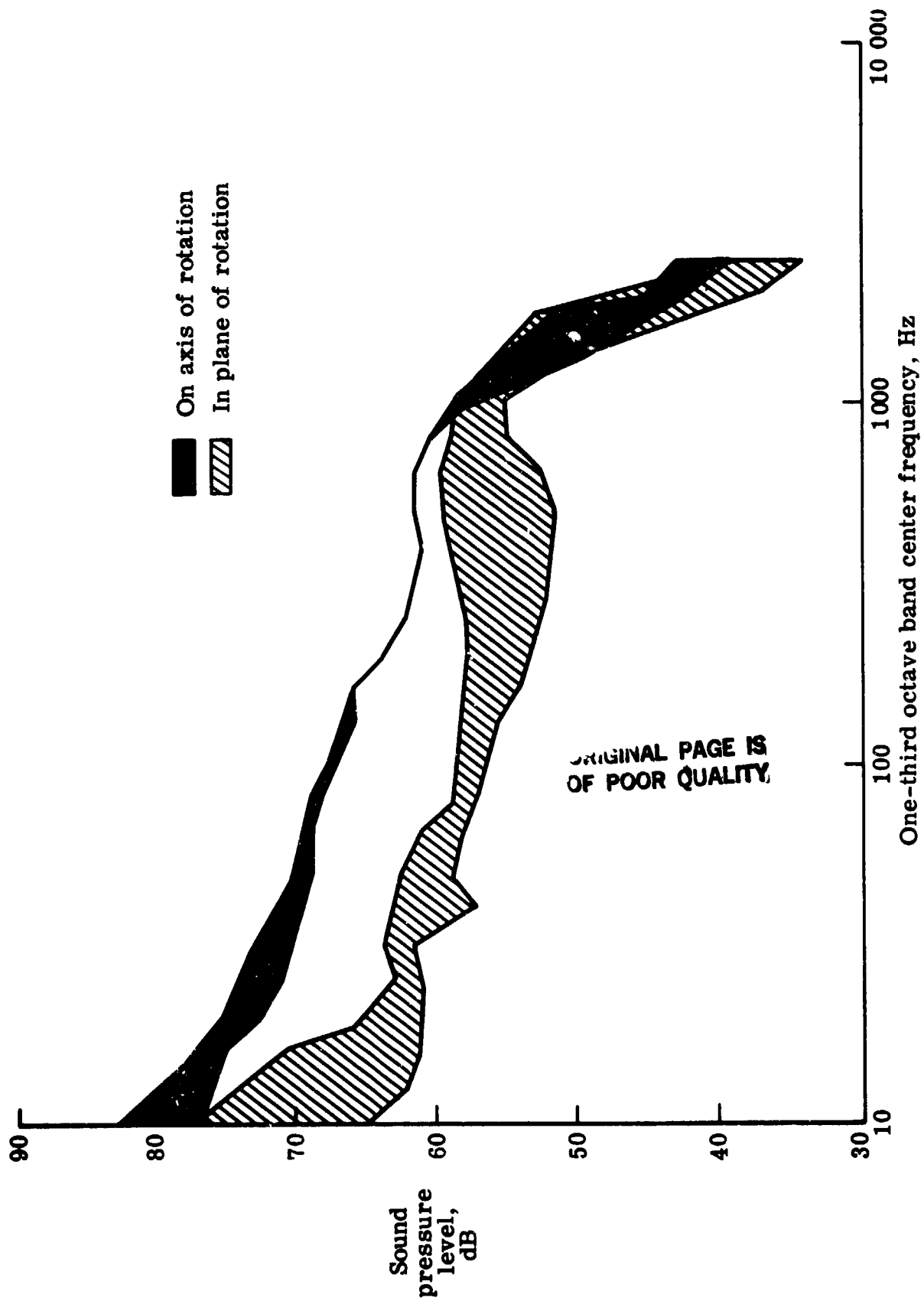


Figure 13.- One-third octave band spectra of the noise from the WTS-4 machine in two directions and at a distance of 91.5 m. $P = 2.4$ MW, $V = 12$ m/s.

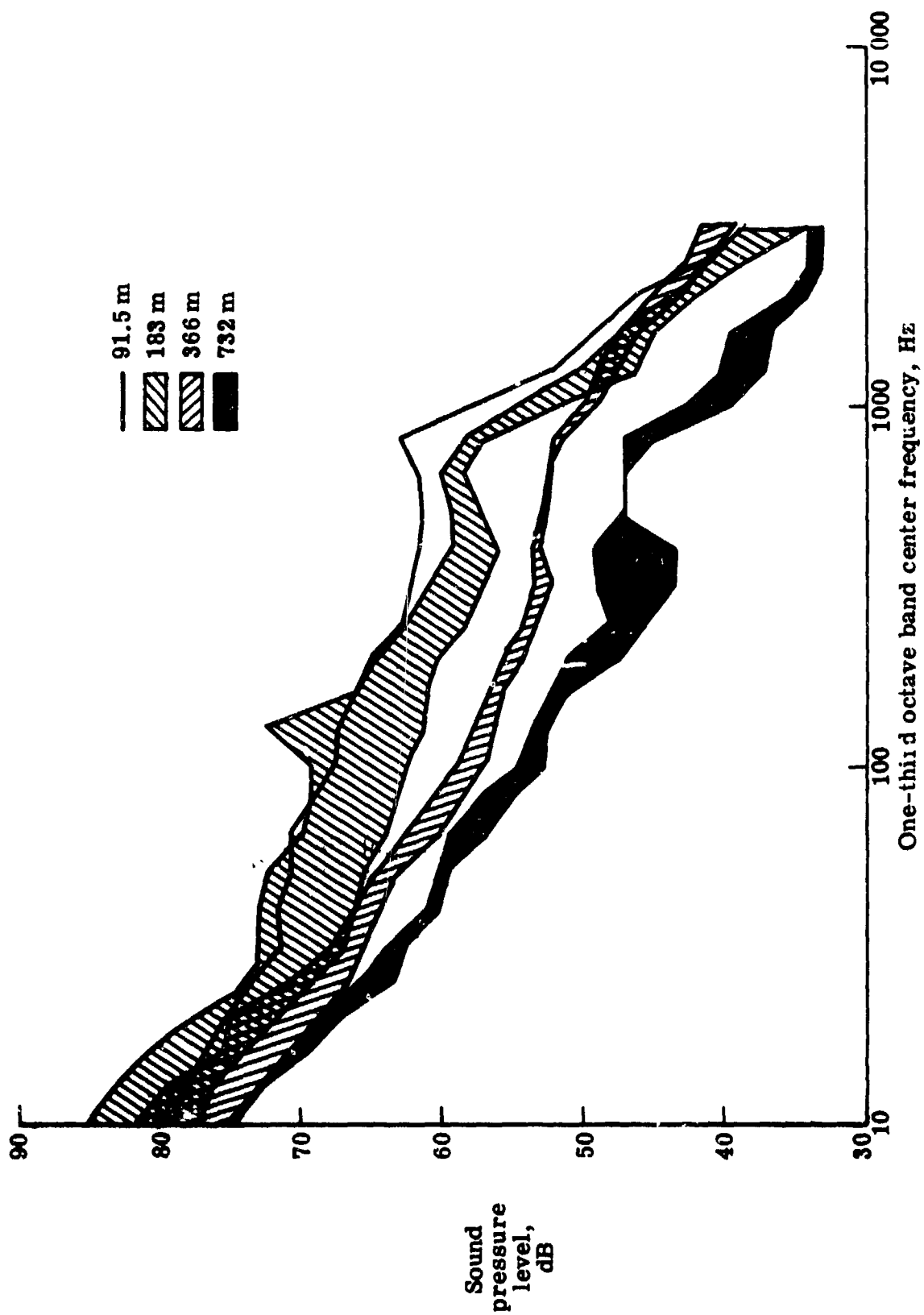


Figure 14.- One-third octave band spectra of the noise from the WTS-4 machine at four distances in the downwind direction $P = 2.0-3.0$ MW, $V = 11-16$ m/s.

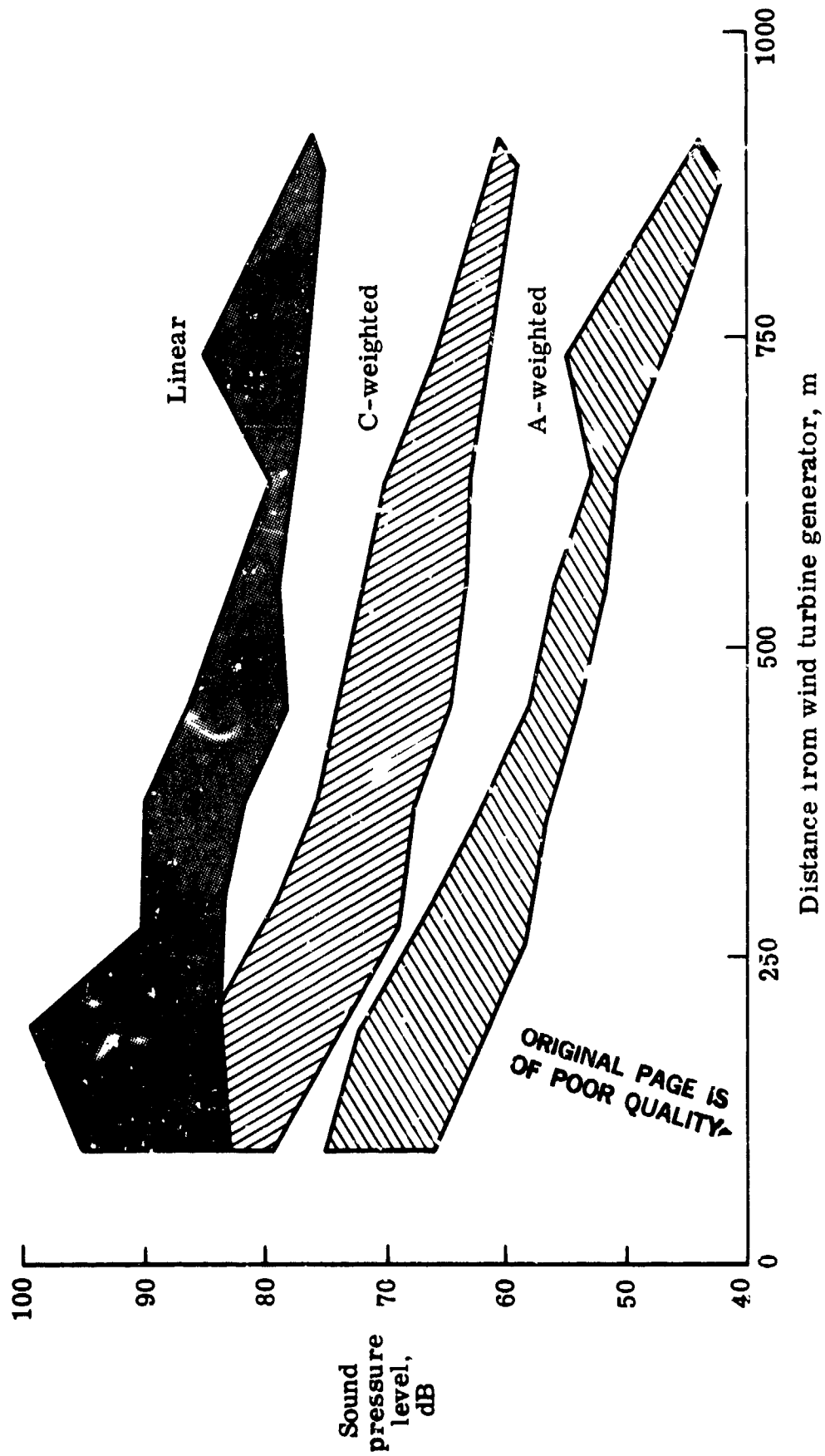


Figure 15.- Ranges of measured sound pressure levels for the WTS-4 wind turbine generator for a range of azimuth angles from zero to 300° for three different frequency weightings. $P = 1.0-3.0$ MW, $V = 7.6-17$ m/s.

Machine	Tip speed, m/sec	Blade area, m ²
WTS-4	122.6	208
MOD-2	83.8	197
MOD-OA	80.0	32

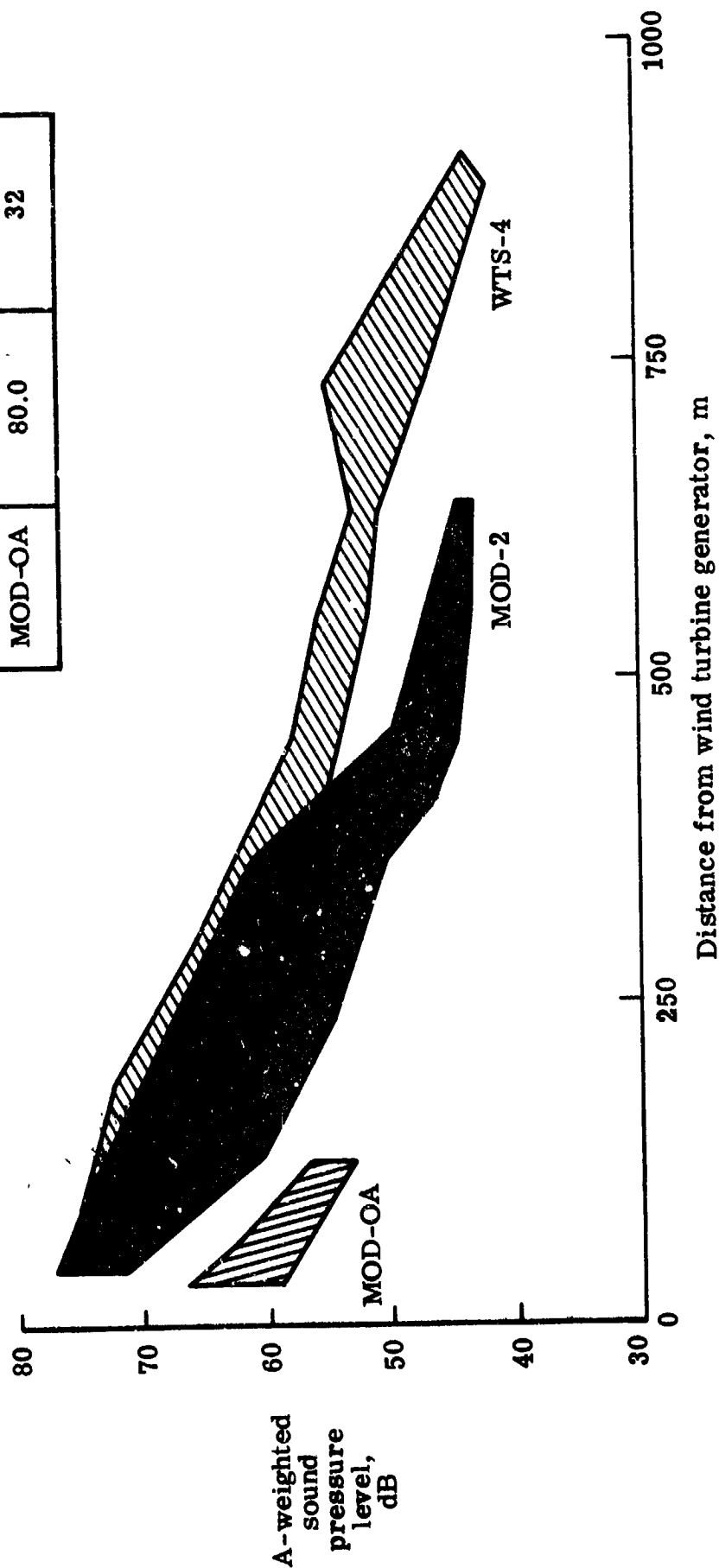


Figure 16.- Comparisons of the measured A-weighted sound pressure levels for three different wind turbine generators as a function of distance.

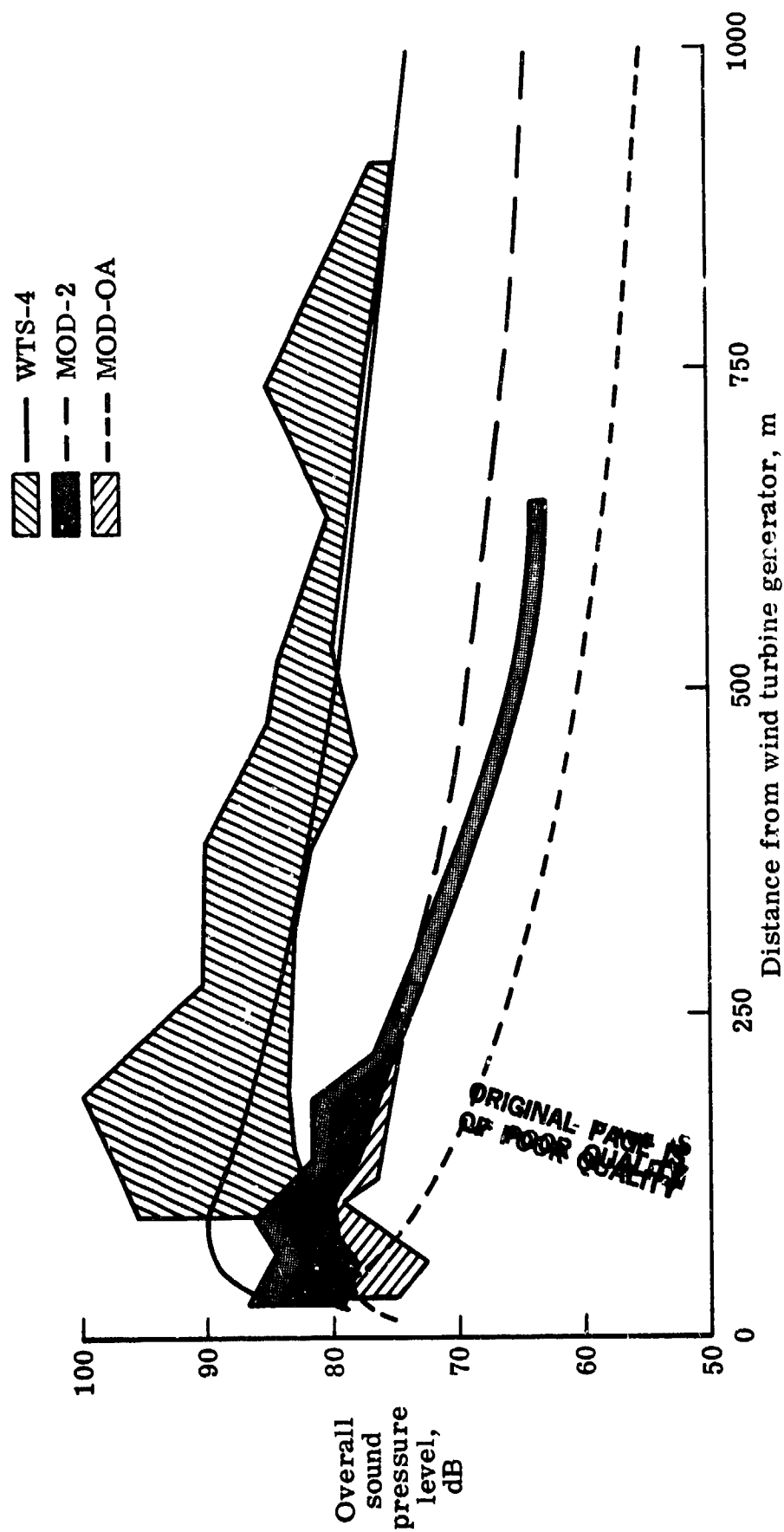


Figure 17.- Comparisons of the overall sound pressure levels for three different wind turbine generators as a function of distance. Shading represents measured values whereas the curves represent predicted values by the method of Ref. 8.

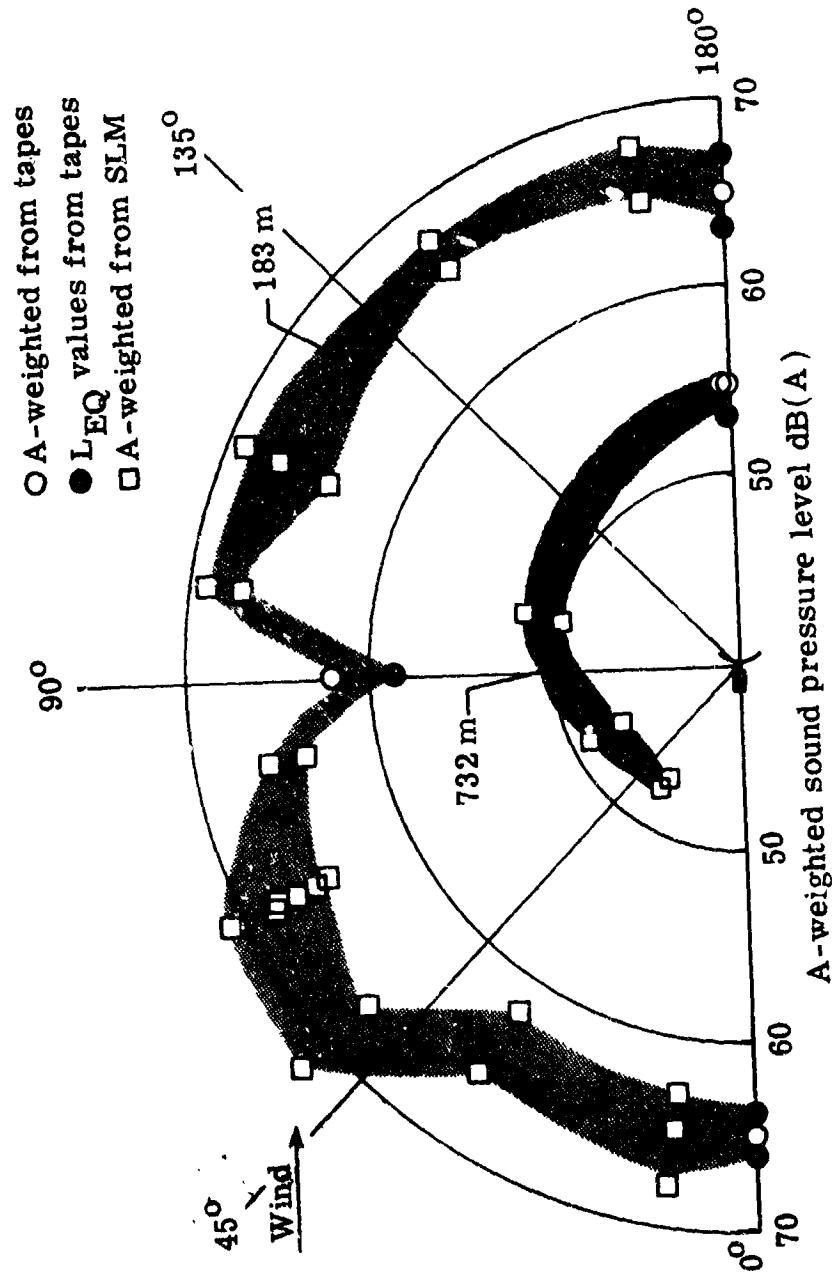


Figure 18.- A-weighted sound pressure levels for the WTS-4 machine as a function of azimuth angle at two different distances. $P = 1.0$ -3.0 MW, $V = 7.6$ -17 m/s.

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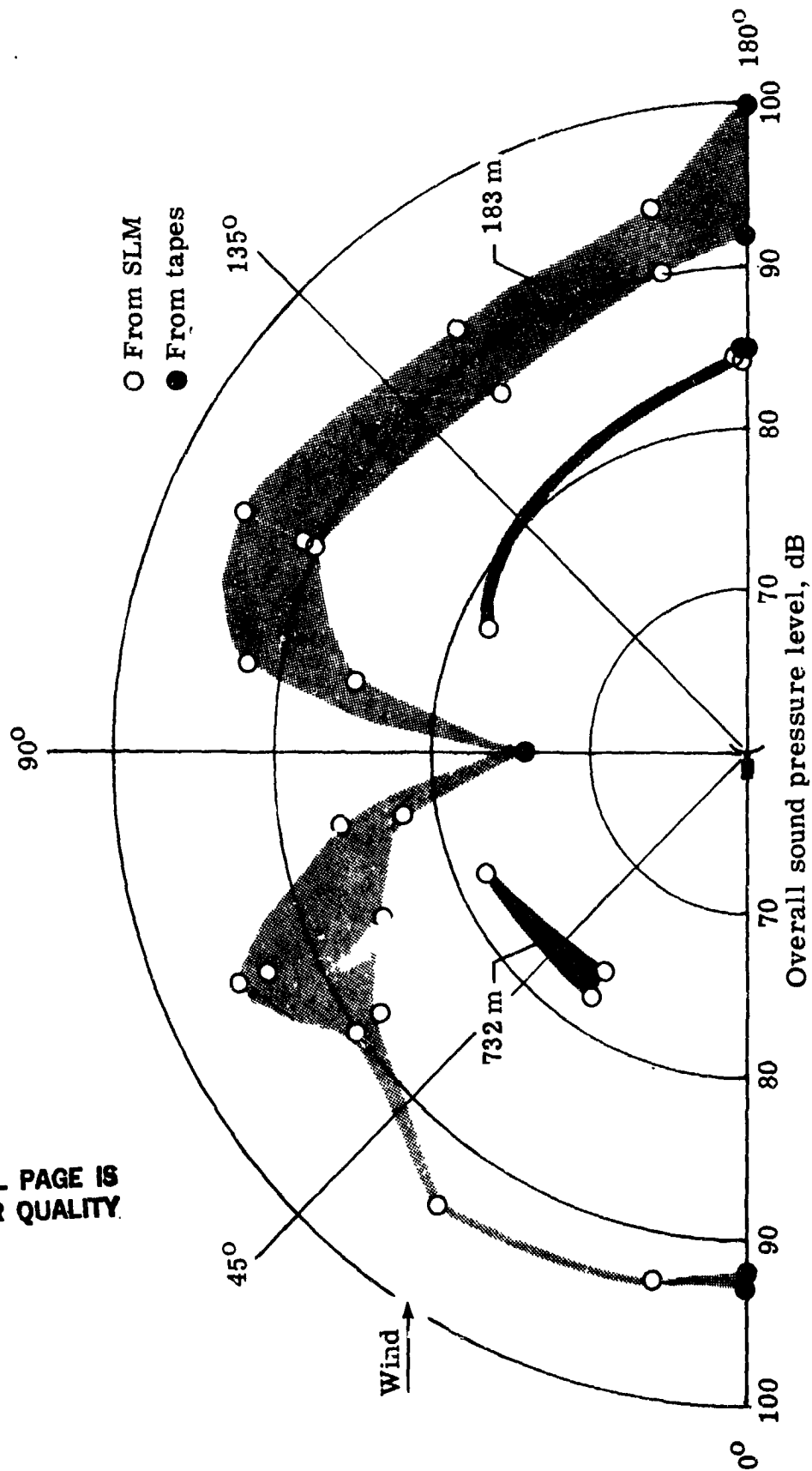


Figure 19.- Overall sound pressure levels for the WTS-4 machine as a function of azimuth angle at two distances. $P = 1.0-3.0$ MW, $V = 7.6-17$ m/s.

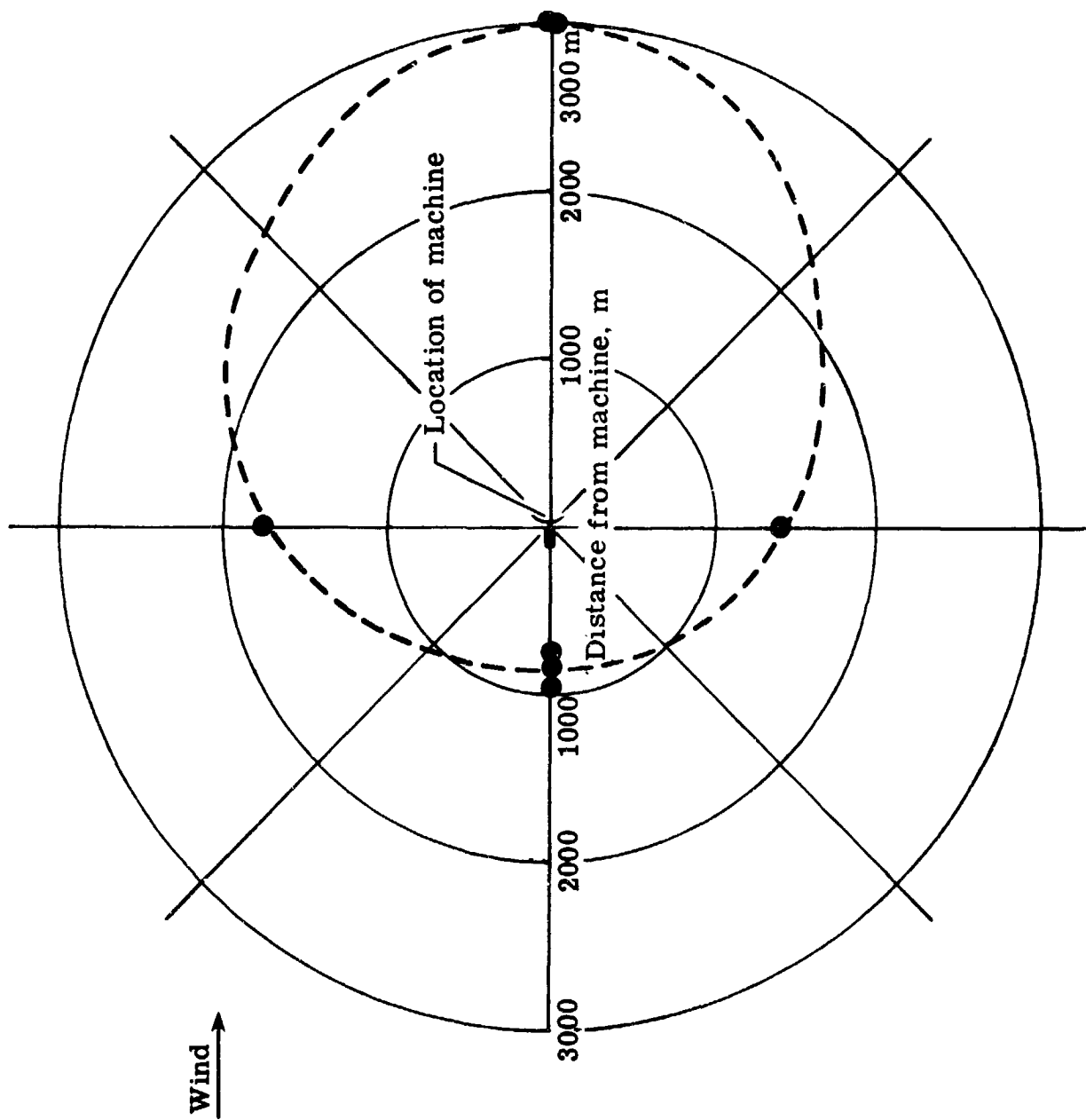


Figure 20.- Perception distance observations for the WTS-4 machine. $P = 2.3-4.2$ MW,
 $V = 12-19$ m/s.

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16. Abstract <p>Measurements and observations of the noise from the WTS-4 wind turbine generator have been made for a range of wind velocities of 7.6 m/s to 21 m/s and for a range of power outputs from 1.0 to 4.2 MW. Both broad band and narrow band data were obtained for various azimuth angles and for a range of distances from the machine.</p> <p>Peaks in the instantaneous pressure time histories are generated as each blade passes through the tower wake and these peak amplitudes vary widely in level. Associated low frequency components, at multiples of the blade passage frequency are identifiable below 100 Hz and for all directions and distances at which measurements were made. Noise components associated with the electric generator, the hydraulic pumps and the cooling fans are identified in near field measurements but only the fan noise is observable in the far field.</p> <p>Perception distances varied from about 900 m upwind to 1600 m crosswind to 2900 m downwind. The low frequency components were significant for perception downwind but only the broad band components were perceived at extreme distances upwind and crosswind.</p>					
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